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RESEARCH MEMORANDUM

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TYPE COMBUSTOR AT MACH NUMBERS OF 1.50 TO 2.16

By Donald P. Hearth and Eugene Perchonok

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NATIONAL ADVISORY COMMITTEE
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SUMMARY

An investigation was conducted in the 8- by 6-foot supersonic wind tunnel to evaluate the performance of a 16-inch ram-jet engine using a can-type-combustor configuration. Data were obtained over a fuel-air-ratio range of from 0.018 to 0.070 at free-stream Mach numbers of 1.50, 1.79, 1.98, 2.10, and 2.16. Angle-of-attack data to 10° are presented at Mach numbers 1.50, 1.79, and 1.98.

Results of this investigation indicated that the combustion efficiencies were generally unaffected by free-stream Mach number and varied between 60 and 90 percent with JP-4 fuel. Combustor operation at 10° angle of attack was satisfactory except under subcritical diffuser operaion at Mach number 1.98. The minimum specific fuel consumption (based on propulsive thrust) was 3.4 and occurred at Mach number 1.98. Gains in propulsive thrust by subcritical inlet operation were obtained only at free-stream Mach numbers below 1.98. Analysis of the pressure pulsations in the burning engine indicated the predominant frequency was 225 cycles per second for which amplitudes as high as 30 percent of the internal total pressure were observed.

INTRODUCTION

Most ram-jet combustor development is undertaken in direct-connect facilities. The resulting combustors usually provide acceptable engine operation under critical and supercritical diffuser conditions. However, few combustors developed in this manner operate satisfactorily, if at all, when combined with a supersonic inlet either at angle of attack or during the inlet pulsing associated with subcritical diffuser operation.

A can-combustor configuration was investigated in the Lewis 8- by 6-foot supersonic wind tunnel in a 16-inch ram-jet engine (refs. 1 and 2). Equipped with this combustor and using propylene oxide as fuel, the engine exhibited little sensitivity to angle of attack or subcritical diffuser instability. However, combustion with gasoline was unsatisfactory and even with highly volatile propylene oxide the combustion efficiencies were generally low.

As part of an over-all NACA program on combustion-chamber design, experiments in a direct-connect facility indicated that the performance of the can-type combustor utilized in the previous tests on the 16-inch ram-jet engine could be considerably improved through modifications of the fuel-injection system (refs. 3 and 4). The tests of reference 3 were made at an inlet temperature of 600° F. Reduction to 150° F (in the range generally experienced in the 8- by 6-ft tunnel) resulted in only a small drop in the efficiency level and little change in the general performance trends (ref. 4).

The modified combustor was then installed in the 16-inch ram-jet engine and again investigated in the 8- by 6-foot supersonic wind tunnel. In addition to combustor performance, the diffuser and the engine were evaluated at free-stream Mach numbers beyond the limit of the facility (Mach number 2.0) by use of an inclined plate producing a flow expansion ahead of the inlet (see ref. 5). As part of the investigation, a preliminary frequency-spectrum evaluation was made indicating amplitudes of the pressure fluctuations occurring in the burning engine. Data were taken at free-stream Mach numbers of 1.50, 1.79, 1.98, 2.10, and 2.16 and at angles of attack to 10°.

SYMBOLS

The following symbols are used in this report:

A area, sq ft

C_D external drag coefficient, $\dfrac{D}{q_0 A_{max}}$

C_{F-D} propulsion thrust coefficient, $\dfrac{F-D}{q_0 A_{max}}$

D external drag, lb

F internal thrust, lb

$F-D$ propulsion thrust, lb

f fuel flow, lb/hr

f/a fuel-air ratio

M Mach number

m mass flow, ρAV, slugs/sec

P	total pressure, lb/sq ft
p	static pressure, lb/sq ft
q	dynamic pressure, $\frac{\gamma}{2}pM^2$, lb/sq ft
r	radius, ft
SFC	specific fuel consumption, $\frac{f}{F-D}$, $\frac{lb/hr}{lb}$
T	total temperature, °R
V	velocity, ft/sec
α	angle of attack, deg
γ	ratio of specific heats for air
ρ	static density, slug/cu ft
η_b	combustion efficiency
τ	total-temperature ratio across engine, $\frac{T_6}{T_0}$

Subscripts:

max	maximum
t	total
x	air-flow measuring station
0	free stream
3	combustion-chamber inlet
5	nozzle entrance
6	engine exit

APPARATUS AND PROCEDURE

The 16-inch ram-jet engine was mounted in the 8- by 6-foot supersonic wind tunnel as shown in figure 1. Engine details are indicated in figure 2(a). The supersonic diffuser was designed such that the single oblique shock generated by the 25°-half-angle spike would fall slightly

outside the cowl lip at a free-stream Mach number of 1.8 and slightly inside at a Mach number of 2.0. (A 45° oblique shock would intersect the cowl lip.) A more detailed discussion of the supersonic diffuser and the engine installation is included in references 1 and 2.

The combustor (fig. 2(b)) investigated in the engine was of exactly the same design as that reported in reference 3 (configuration I) and in reference 4. Except for the sleeve and fuel-injector arrangement, the can was identical with the one used in references 1 and 2. Surface open area of the can-type flame holder was 133 percent of the combustion-chamber cross-sectional area.

The fuel-injection modification was such that all the fuel was injected 17 inches upstream of the flame holder. Two fuel manifolds were utilized, one for each of the flow annuli formed by the mixture control sleeve. Six commercial spray nozzles injected fuel into the inner (primary) zone while 16 nozzles sprayed fuel into the outer (secondary) zone. The primary and secondary spray nozzles were rated at 30 and 39 gallons per hour, respectively (at 100 lb/sq in.).

A simple conical convergent nozzle was used as the jet exit. This nozzle had an area contraction ratio of 0.71 and an exit (throat) area of 0.990 square foot.

In order to investigate the engine performance at test Mach numbers in excess of the facility limit (2.0), a sharp-edged plate with its surface parallel to the engine axis was mounted ahead of the engine inlet (fig. 1). Because the stream flow would expand over the leading edge of the plate as it was raised to angle of attack, the local air velocity could be raised above the test section value. Local inlet Mach numbers of up to 2.16 were obtained at a tunnel Mach number of 2.0 by this technique. A more detailed discussion of the "inclined plate" and its adequacy as a test technique is presented in reference 5.

Inlet-pressure recovery and air-flow characteristics of the engine were obtained from a previously calibrated static- and total-pressure rake at the air-flow measuring station x (see fig. 2(a)). Exit total pressure was generally obtained from the total-pressure tail rake shown. Combustor and engine performance were calculated from these measurements and an exit total temperature calculated from continuity relation. In order to vary the amount of heat addition required for a given inlet-operating condition, an exit plug (fig. 1) was used in one phase of the investigation. For this case, combustor performance was calculated by use of the relation $\frac{M_3\sqrt{\tau}}{A_6} \approx$ constant (ref. 6).

Frequency and amplitude of the pressure fluctuations in the burning engine were measured with dynamic pressure pickups and a commercial harmonic frequency analyzer capable of measuring pressure amplitudes in a frequency range of from 50 to 1000 cycles per second. The pickups were located at the air-flow measuring station, the combustion-chamber entrance, and at the nozzle entrance.

DISCUSSION OF RESULTS

Diffuser Performance

Presented in figures 3, 4, and 5 is the engine diffuser performance at free-stream Mach numbers of 1.50, 1.79, 1.98, 2.10, and 2.16. Results consistent with those reported in references 1 and 2 for this same inlet configuration were noted. Above $M_0 = 1.98$, the general trends of diffuser recovery with M_3 were similar to that at $M_0 = 1.98$, but the critical pressure recovery fell off rapidly. At Mach numbers of 1.98 and above, the spike-generated oblique shock fell within the cowl lip, and for critical diffuser operation, not all the entering flow passed through the oblique shock before encountering the normal shock. Figure 3 also indicates a progressively greater decrement in subcritical pressure recovery as the Mach number was raised to 1.98. Above this Mach number, the subcritical pressure recovery decrease appeared unaffected by free-stream Mach number. There was no stable subcritical range at $M_0 = 1.98$ and above for this diffuser in conjunction with the burning ram-jet engine.

Figure 5 indicates the effect of free-stream Mach number on the velocity profiles at the air-flow measuring station. Since it was observed that the effect of diffuser operation was, for all the Mach numbers, similar to that presented in reference 2 for Mach number 1.8, data are presented for only critical diffuser operation. As free-stream Mach number was increased, the sharpness of the radial profiles appears to have been reduced. However, a circumferential variation in the profiles developed at Mach numbers above 1.98.

Combustor Performance

Two fuels, JP-4 and gasoline, were initially investigated in the combustor and a study was made to determine which fuel resulted in superior combustion efficiency characteristics. While maintaining critical diffuser operation by adjusting the secondary fuel flow, the amount of fuel introduced through the primary injector was systematically varied. The resulting combustion-efficiency data are presented in figure 5 as a function of primary fuel-air ratio (ratio of primary fuel flow to total air flow). The lean blow-out limit for both fuels was found to be at a

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primary fuel-air ratio of 0.009, and a peak combustion efficiency of 0.75 was obtained with both fuels. However, whereas the peak efficiency for gasoline occurred at 0.010 and was close to the lean blow-out limit, the maximum for JP-4 fuel occurred at 0.013. A severe penalty in combustion efficiency was encountered with gasoline at other than the fuel-air-ratio value for peak efficiency, while with JP-4 fuel, reasonable tolerance was available if the primary fuel-air ratio was not set at the exact value corresponding to peak efficiency. Consequently, JP-4 fuel was used in the remainder of the investigation, and to avoid lean blow-out, the combustor was operated at a primary fuel-air ratio of approximately 0.015 ± 0.002.

As part of this study, the water-cooled exit plug shown in figure 1 was used to vary the combustion-chamber-inlet Mach number M_3 independently of the engine fuel-air ratio. Combustion-efficiency data are presented in figure 7 as a function of M_3 at a constant fuel-air ratio of 0.030. Although data were only obtained over a limited range, it appears that the combustion efficiency was essentially insensitive to combustor-inlet velocity.

Presented in figure 8 is the general combustor performance at free-stream Mach numbers of 1.50, 1.79, 1.98, and 2.16 and at angles of attack from zero to 10°. Data were obtained with the water-cooled tail rake and are presented over a fuel-air-ratio range from 0.015 to 0.075. Combustion efficiencies of from 0.60 to 0.90 and total-temperature ratios approaching 7.0 were obtained. A decrease in efficiency was indicated as the fuel-air ratio was increased to 0.025 and then a continual increase with increasing fuel-air ratio was obtained. Since a change in over-all fuel-air ratio resulted in a change in fuel distribution, the results of figure 7 and 8 indicate that, for this combustor, fuel distribution was a more critical combustion-efficiency parameter than average combustor-entrance Mach number.

Raising the engine to angle of attack, which resulted in changes of internal air flow and, consequently, local fuel-air-ratio distributions, generally dropped the combustion efficiency, especially at the higher fuel-air ratios. Except for an angle of attack of 10° at a free-stream Mach number of 1.98, no difficulty in burning was encountered under subcritical diffuser operation. For these conditions it was found that combustion could be sustained only by maintaining continuous spark ignition and in spite of this aid, the combustion remained erratic and unsteady.

A comparison of combustor performance at the various free-stream Mach numbers indicates that there was little effect of free-stream Mach number on the general trends of combustion efficiency with fuel-air ratio. Although the combustor pressure levels were somewhat different for the various Mach numbers (as indicated on the individual figures),

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it is felt that these pressures were in the range where small changes in pressure level have little effect on combustion efficiency.

A comparison is presented in figure 9 between the combustion efficiencies obtained in the present investigation and those obtained with the same combustor configuration in a connected pipe facility (ref. 4). It is interesting to note that the trends for the two sets of data are generally similar and that, except for subcritical inlet operation ($f/a > 0.038$) and within experimental accuracy, even the absolute values are in agreement. At a fuel-air ratio greater than 0.038 the connected-pipe combustion efficiencies were appreciable greater than those observed in the tunnel. The tunnel data were obtained under diffuser pulsing conditions. This discrepancy in combustion efficiency may have, in addition to the difference in diffuser operation, been due to differences in the subsonic diffusers themselves.

In order to evaluate the effect of combustion-chamber length on combustion efficiency, the length of the combustion chamber plus exit nozzle was reduced from 7.5 to 5.5 feet. Results obtained with the short configuration are presented in figure 10 and are compared with the results obtained with the original combustion-chamber length. As expected, the combustion efficiency was reduced because of the shorter length available in which to burn the fuel. The maximum value of the decrease was approximately 8 percent.

Meager data are available on pressure pulsations in burning ram-jet engines. Some of these data are presented in reference 2 for the engine reported herein. Since the data of reference 2 were reliable only to frequencies in the range below 100 cycles per second, the frequency spectrum range was extended in this study. Pressure traces in the frequency range from 50 to 1000 cycles per second were obtained at three engine locations with commercially available pickups and recorded with a commercial harmonic wave analyzer. Representative results of this survey are presented in figure 11.

The data of figure 11 which are for a free-stream Mach number of 2.16, as well as similar data obtained at other Mach numbers, indicated the following predominant frequencies: 70 $\pm$10, 225 $\pm$25, and 450 $\pm$50 cycles per second. High-speed motion pictures of the subcritical inlet shock movement indicated oscillations of 225 cycles per second, the most predominant of the subcritical pulsation frequencies (fig. 11). This same predominant subcritical frequency is apparent, moreover, at all three engine stations surveyed.

The variation of the pressure amplitudes with increasing fuel-air ratio (thus causing subcritical inlet operation) is presented in figure 12 for a frequency of 225 cycles per second and various Mach numbers. Few pulsations of any significance were evident until the diffuser became

subcritical. Then a marked rise in the pressure amplitudes occurred. Peak amplitudes of approximately 6 pounds per square inch (about 30 percent of the total pressure) were observed at the combustion-chamber inlet station. Although figure 12 indicates reduction of the peak amplitudes upstream and downstream of the combustion-chamber inlet only at 1.98, other data not shown indicated reduction for all the Mach numbers. Free-stream Mach number has but a very small effect on the amplitudes observed in the supercritical region and, within the accuracy of the data, no significant effect on the subcritical oscillation amplitudes. Increasing free-stream Mach number did, however, narrow the subcritical region in which the large amplitudes occurred.

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Engine Performance

Engine-performance data obtained with the modified can-type combustor are presented in figure 13. Data are shown for free-stream Mach numbers of 1.50, 1.79, 1.98, and 2.16. In order to present the data on a propulsive thrust basis, the following external drag, C_D, values were taken from reference 1 for Mach numbers to 1.98 and were extrapolated for the 2.16 data:

M_0	Mass-flow ratio						
	1.000	0.920	0.900	0.800	0.777	0.700	0.600
1.50	-----	-----	-----	-----	0.210	0.237	0.272
1.79	-----	0.187	0.194	0.230	.239	.265	.300
1.98	0.174	.210	.219	.265	.275	.308	-----
2.16	.172	.214	.224	.275	.285	.320	-----

At all free-stream Mach numbers, the specific fuel consumption was minimum under critical diffuser operation. Although there was a marked leveling off of the propulsive thrust coefficient at combustion-chamber-inlet Mach number less than critical, slight thrust gains could be realized by subcritical operation at Mach numbers below design (1.50 and 1.79). Although the jet thrust also increased subcritically at Mach number 1.98 and above, the magnitude of the additive drag was sufficient to prevent any propulsive thrust gains.

Critical engine performance is summarized in figure 14. The minimum value of specific fuel consumption (3.4 lb/(hr)(lb thrust)) and maximum value of propulsive thrust coefficient (0.59) occurred at a Mach number of 1.98. Although the nozzle pressure ratio continued to increase beyond a Mach number of 1.98, thus raising the engine jet thrust, the inlet

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CI-2

momentum (which must be subtracted to obtain net thrust) increased at a greater rate, thereby causing a decrease in propulsive thrust.

SUMMARY OF RESULTS

The following results were obtained from an investigation conducted on a 16-inch ram-jet engine with a can-type-combustor configuration at free-stream Mach numbers from 1.50 to 2.16 and angles of attack to 10°:

1. Combustion efficiencies generally increased from about 60 percent at a fuel-air ratio of 0.025 to close to 90 percent at 0.075. The effect of flight Mach number on combustion efficiency was small.

2. No difficulty was encountered in maintaining combustion at 10° angle of attack except subcritically at Mach number 1.98.

3. Although the engine jet thrust increased subcritically at all Mach numbers, the additive drag associated with such operation resulted in slight propulsive thrust gains only at free-stream Mach numbers of 1.50 and 1.79.

4. Specific fuel consumption and propulsive thrust for critical inlet operation were minimum (3.4) and maximum (0.59), respectively, at a free-stream Mach number of 1.98.

5. Peak amplitudes of pressure fluctuations in the burning engine were observed at frequencies of 70, 225, and 450 cycles per second. The predominant frequency appeared to be 225 cycles per second at which amplitudes as high as 6 pounds per square inch (30 percent of total pressure) were observed.

Lewis Flight Propulsion Laboratory
        National Advisory Committee for Aeronautics
                Cleveland, Ohio, July 19, 1954

REFERENCES

1. Nussdorfer, T., Wilcox, F., and Perchonok, E.: Investigation at Zero Angle of Attack of a 16-Inch Ram-Jet Engine in 8- by 6-Foot Supersonic Wind Tunnel. NACA RM E50L04, 1951.

2. Perchonok, Eugene, Wilcox, Fred, and Pennington, Donald: Effect of Angle of Attack and Exit Nozzle Design on the Performance of a 16-Inch Ram-Jet at Mach Numbers from 1.5 to 2.0. NACA RM E51G26, 1951.

3. Cervenka, A. J., Perchonok, Eugene, and Dangle, E. E.: Effect of Fuel Injector Location and Mixture Control on Performance of a 16-Inch Ram-Jet Can-Type Combustor. NACA RM E53F15, 1953.

4. Cervenka, A. J., Dangle, E. E., and Friedman, Robert: Effect of Inlet-Air Temperature on Performance of a 16-Inch Ram-Jet Combustor. NACA RM E53I03, 1953.

5. Fox, Jerome L.: Supersonic Tunnel Investigation by Means of Inclined-Plate Technique to Determine Performance of Several Nose Inlets Over Mach Number Range of 1.72 to 2.18. NACA RM E50K14, 1951.

6. Perchonok, Eugene, Sterbentz, William H., and Moore, Stanley H.: Indirect Methods for Obtaining Ram-Jet Exhaust-Gas Temperature Applied to Fuel-Metering Control. NACA RM E7H27, 1948.

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Inclined plate

Air flow

Test section

Water-cooled tail plug
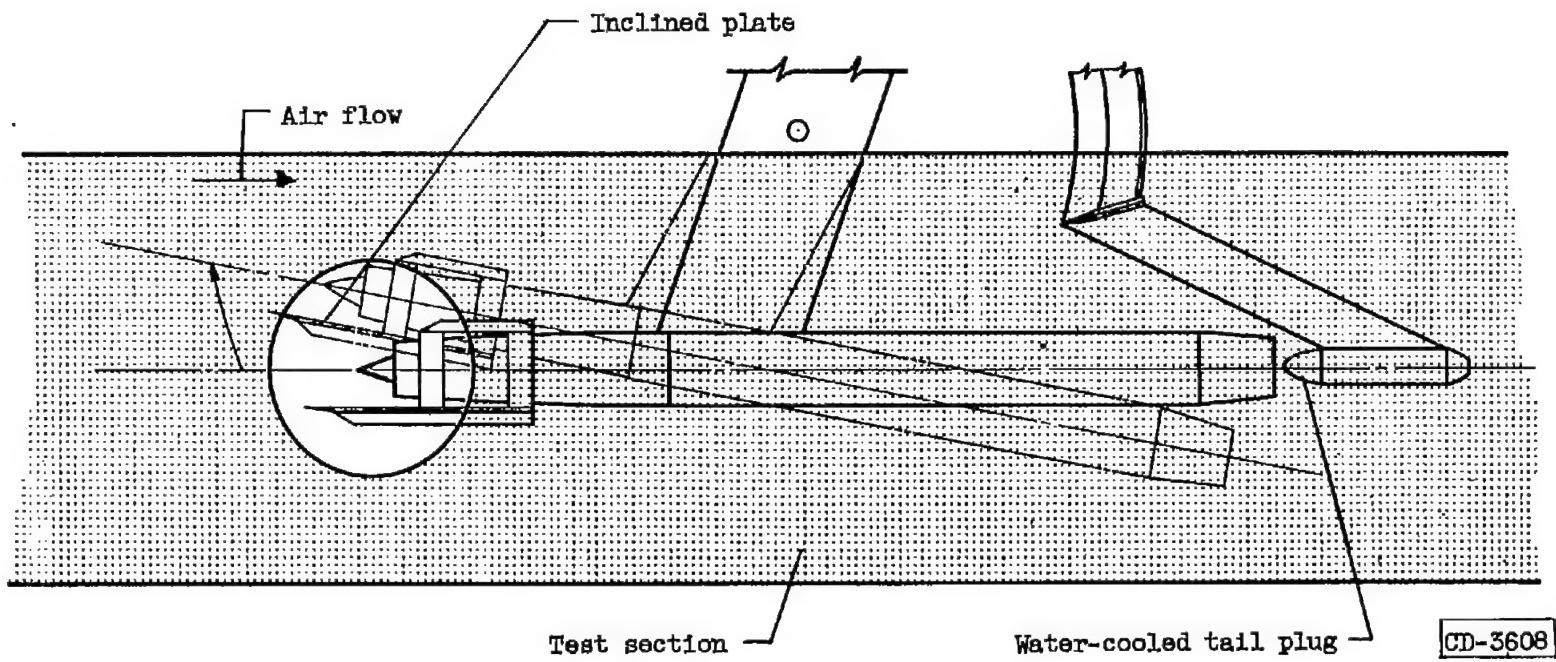
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Figure 1. - Installation of ram-jet engine in 8- by 6-foot supersonic wind tunnel
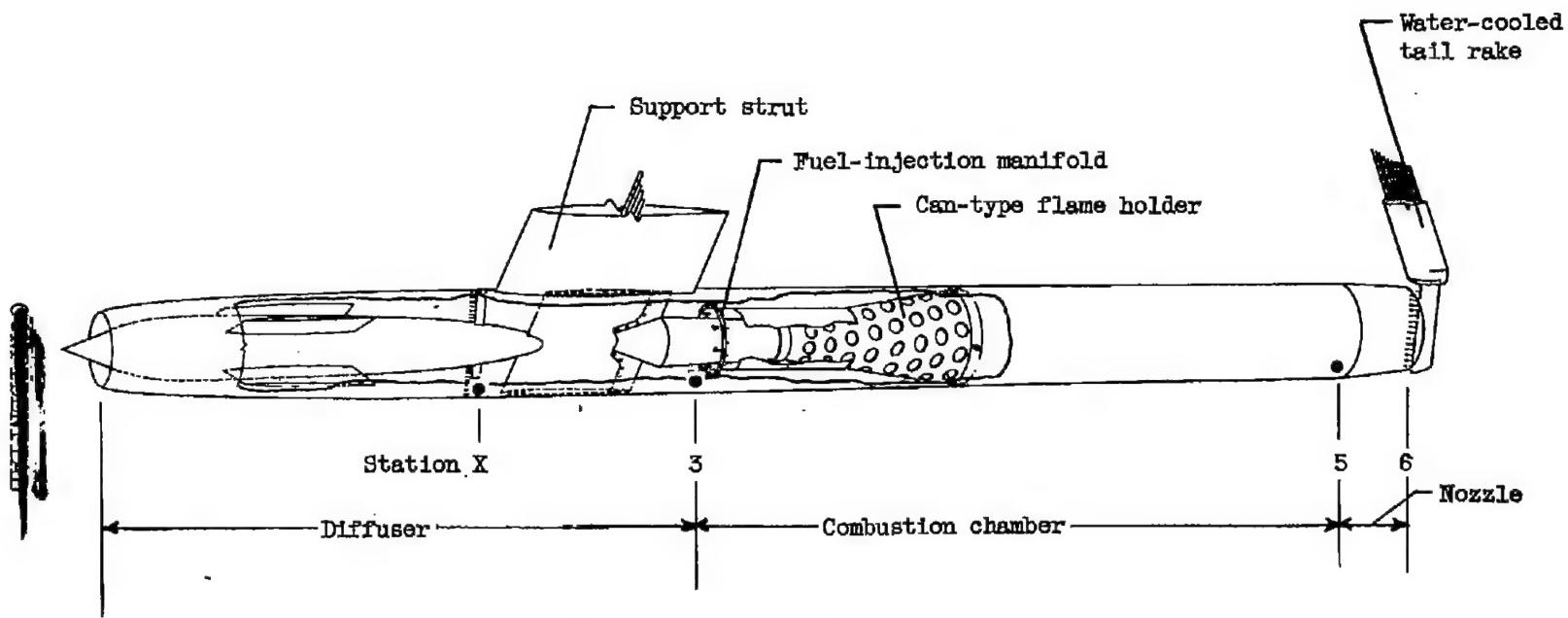
- Location of dynamic pickups

CD-3609

(a) Inner engine details.

Figure 2. - 16-Inch ram-jet engine.

16 Secondary upstream injectors

6 Primary upstream injectors

Pilot

Control sleeve

$1\frac{5}{8}$"

$9\frac{1}{2}$"

$3\frac{7}{8}$"

17"

CD-3610
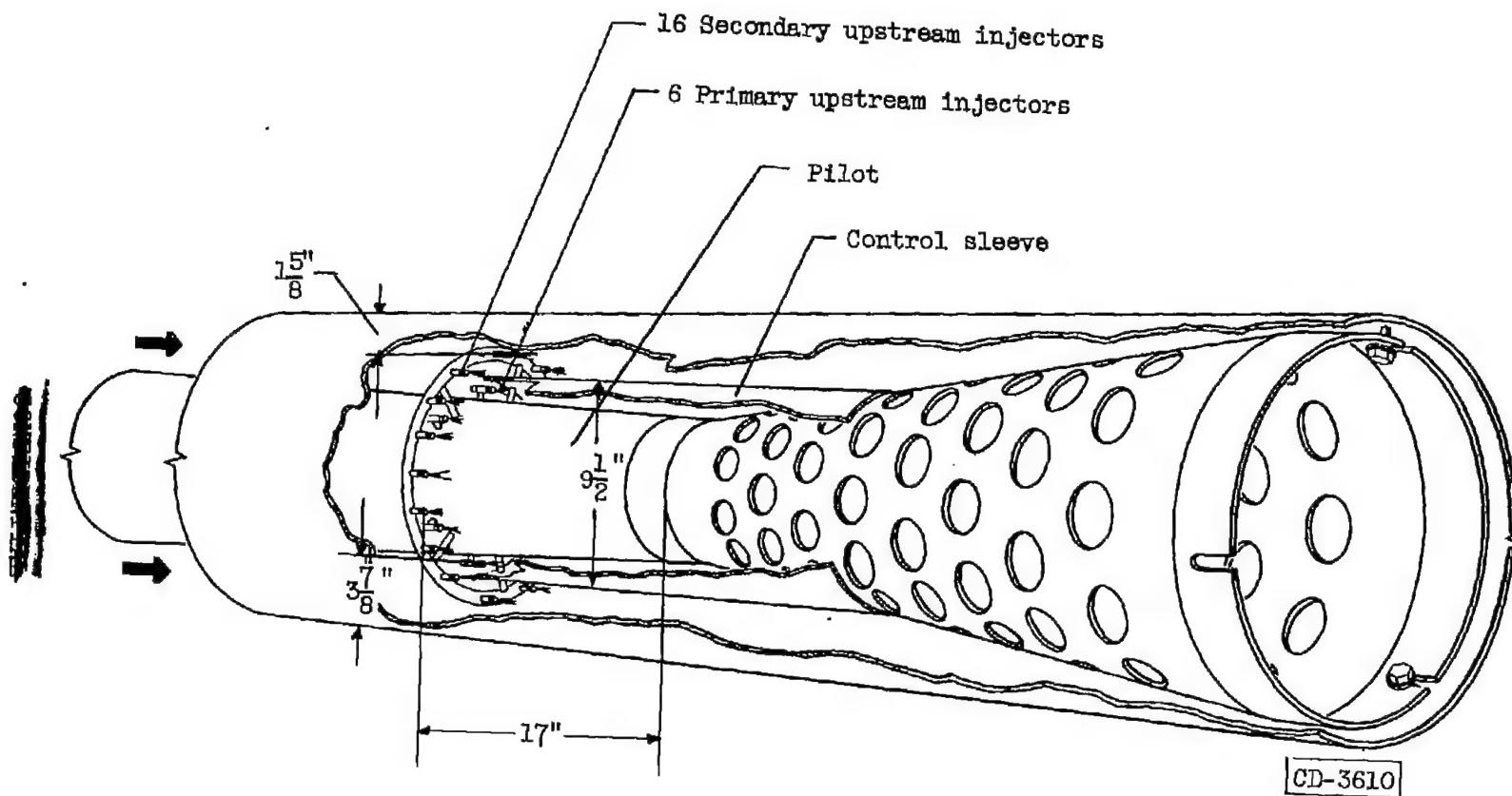
(b) Can-type combustor configuration.

Figure 2. - Concluded. 16-Inch ram-jet engine.

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Angle of attack,
α,
deg
○ 0
□ 5
◇ 10
— — Unstable inlet
operation

1.00

.90

.80

.70

(a) Free-stream Mach number, 1.50.

1.00

.90

.80

.70

(b) Free-stream Mach number, 1.79.

.90

.80

.70

.60

(c) Free-stream Mach number, 1.98.

Diffuser total-pressure recovery, P_x/P_0

.80

.70

.60

(d) Free-stream Mach number, 2.10.

.80

.70

.60

.50

.14   .16   .18   .20   .22   .24   .26   .28
Combustion-chamber-inlet Mach number, M_3

(e) Free-stream Mach number, 2.16.

Figure 3. – Diffuser pressure-recovery characteristics.

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Figure 4. - Diffuser mass-flow characteristics.

(a) Free-stream Mach number, 1.50.

(b) Free-stream Mach number, 1.79.

(c) Free-stream Mach number, 1.98.

(d) Free-stream Mach number, 2.10.

(e) Free-stream Mach number, 2.16.
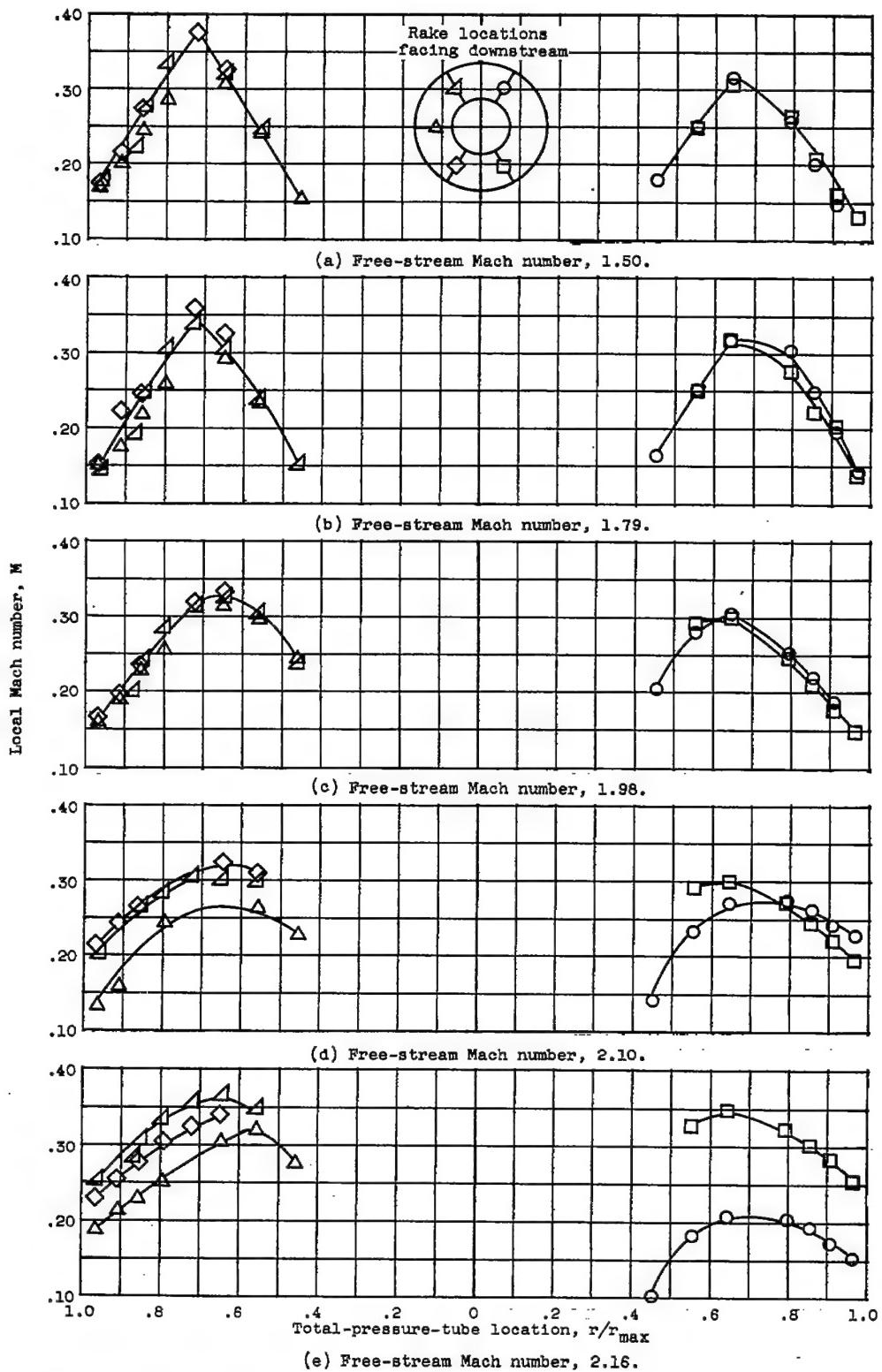
Figure 5. - Mach number profiles at diffuser exit for critical diffuser operation.

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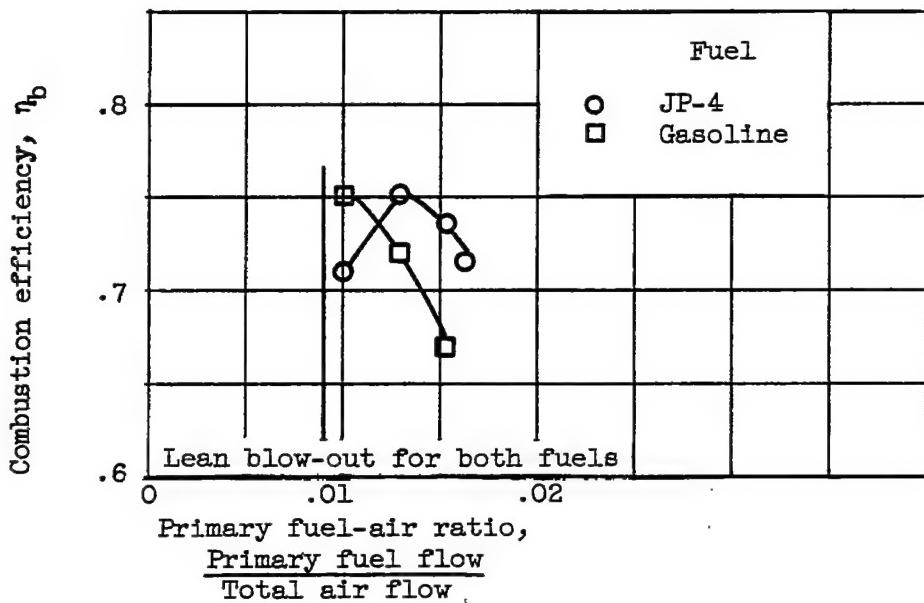
Figure 6. - Effect of primary fuel-air ratio and
fuel type on combustion efficiency. Free-stream
Mach number, 1.98; combustion-chamber inlet Mach
number, 0.197; over-all fuel-air ratio, 0.0385.
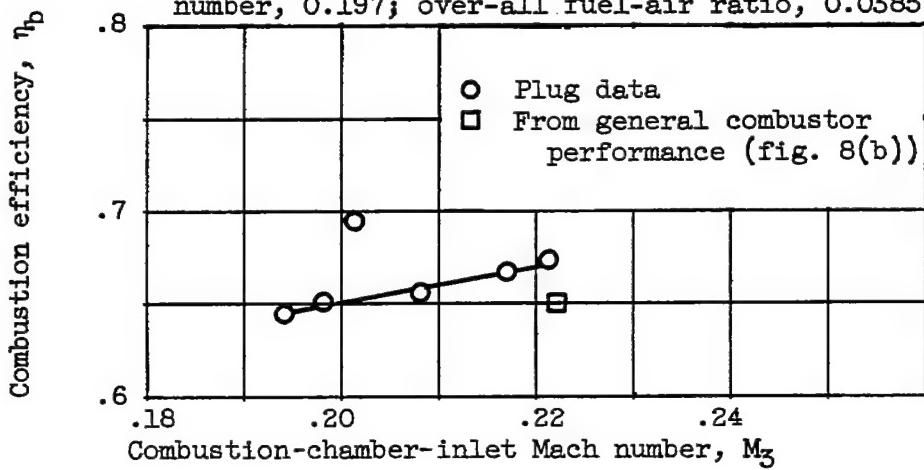
Figure 7. - Effect of combustion-chamber-inlet
Mach number on combustion efficiency for constant
fuel-air ratio of 0.030; free-stream Mach number,
1.79; fuel, JP-4; primary fuel-air ratio, 0.015.
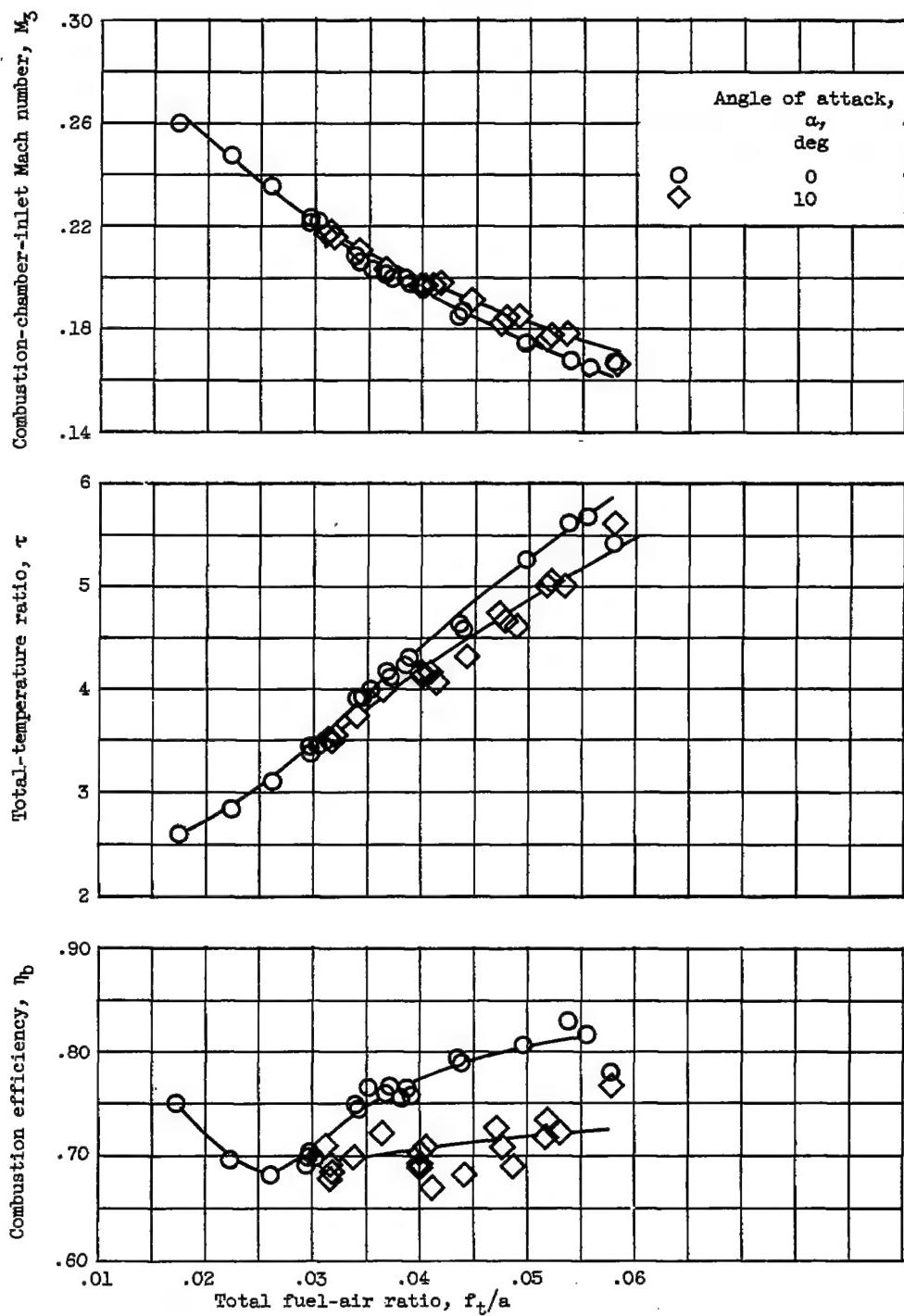
(a) Free-stream Mach number, 1.50; combustion-chamber-inlet pressure,
1800 to 2550 pounds per square foot; combustion-chamber-inlet tempera-
ture, 120° F.

Figure 8. - General combustor performance.

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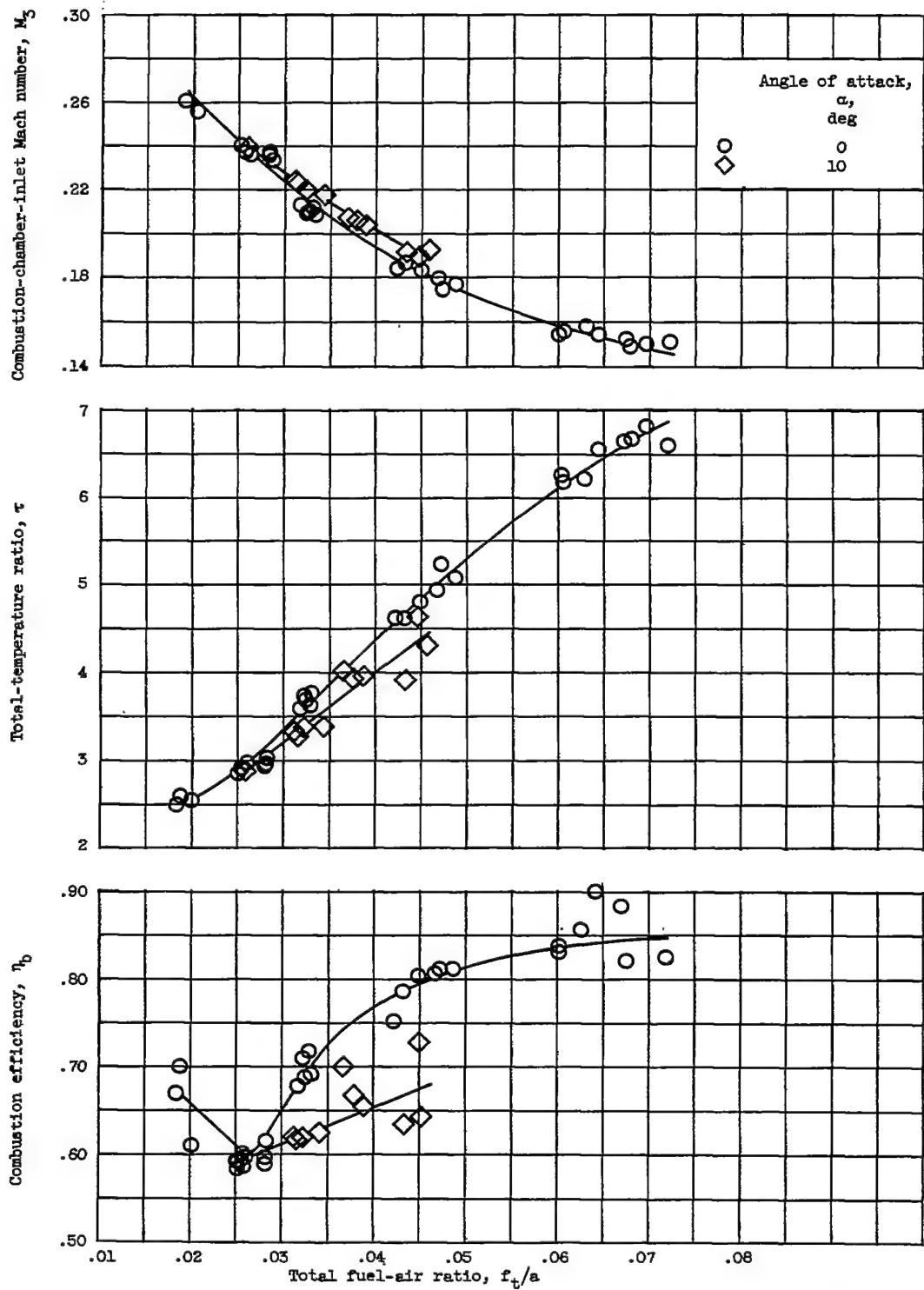
(b) Free-stream Mach number, 1.79; combustion-chamber inlet pressure, 2000 to 2700 pounds per square foot; combustion-chamber-inlet temperature, 135° F.

Figure 8. - Continued. General combustor performance.
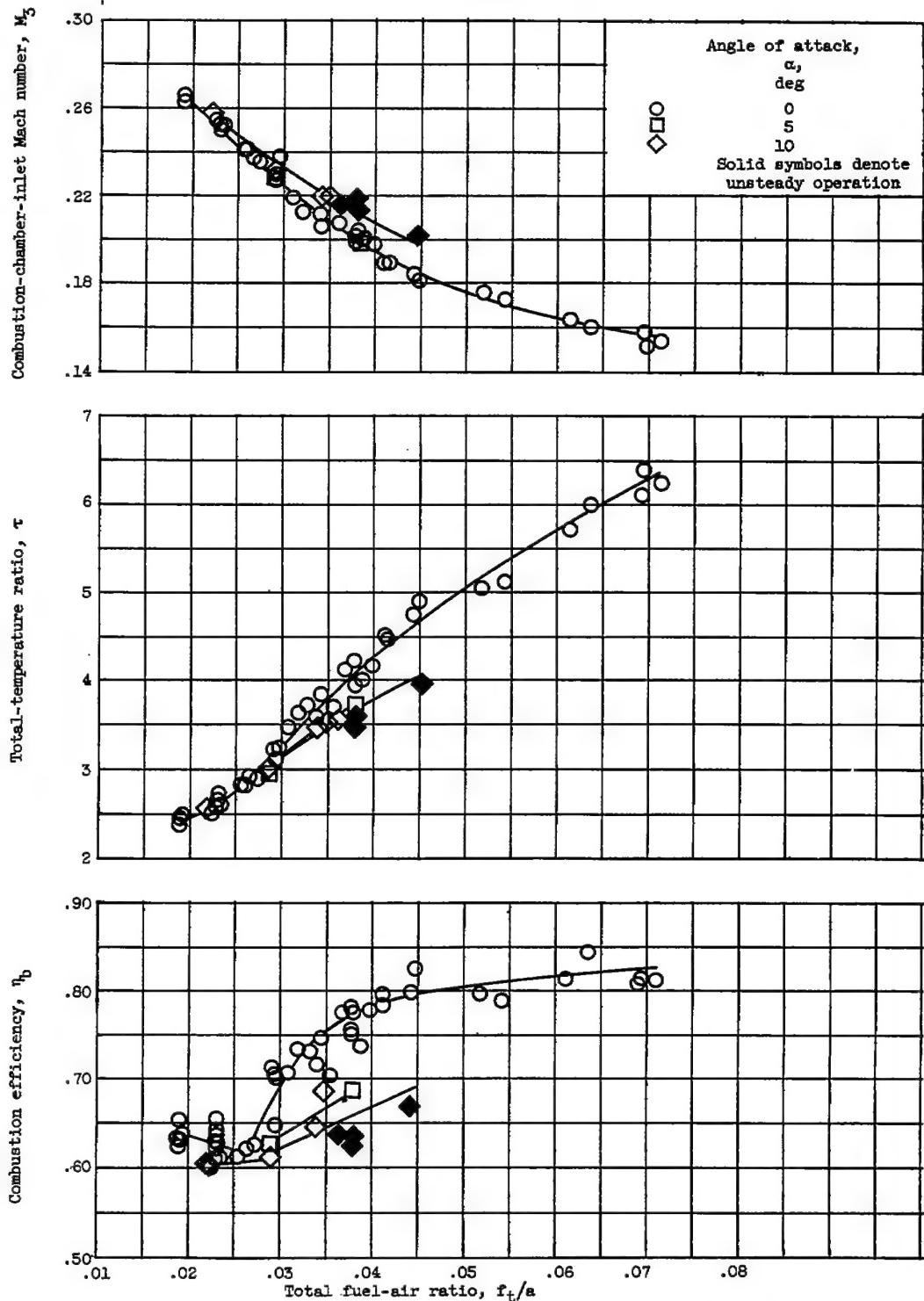
(c) Free-stream Mach number, 1.98; combustion-chamber-inlet pressure, 2000 to 2900 pounds per square foot; combustion-chamber-inlet temperature, 155° F.

Figure 8. - Continued. General combustor performance.
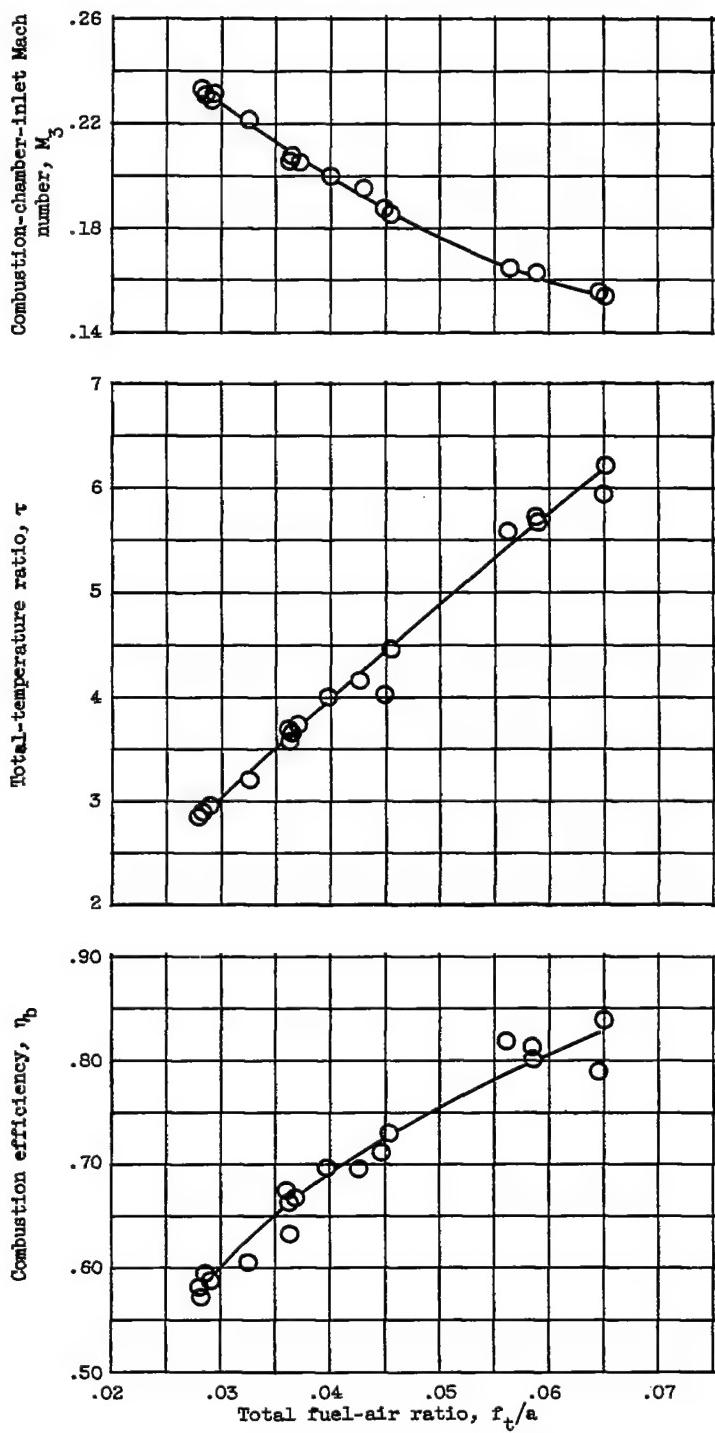
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(d) Free-stream Mach number, 2.16; angle of attack, zero; combustion-chamber-inlet pressure, 2100 to 2700 pounds per square foot; combustion-chamber-inlet temperature, 155° F.

Figure 8. - Concluded. General combustor performance.
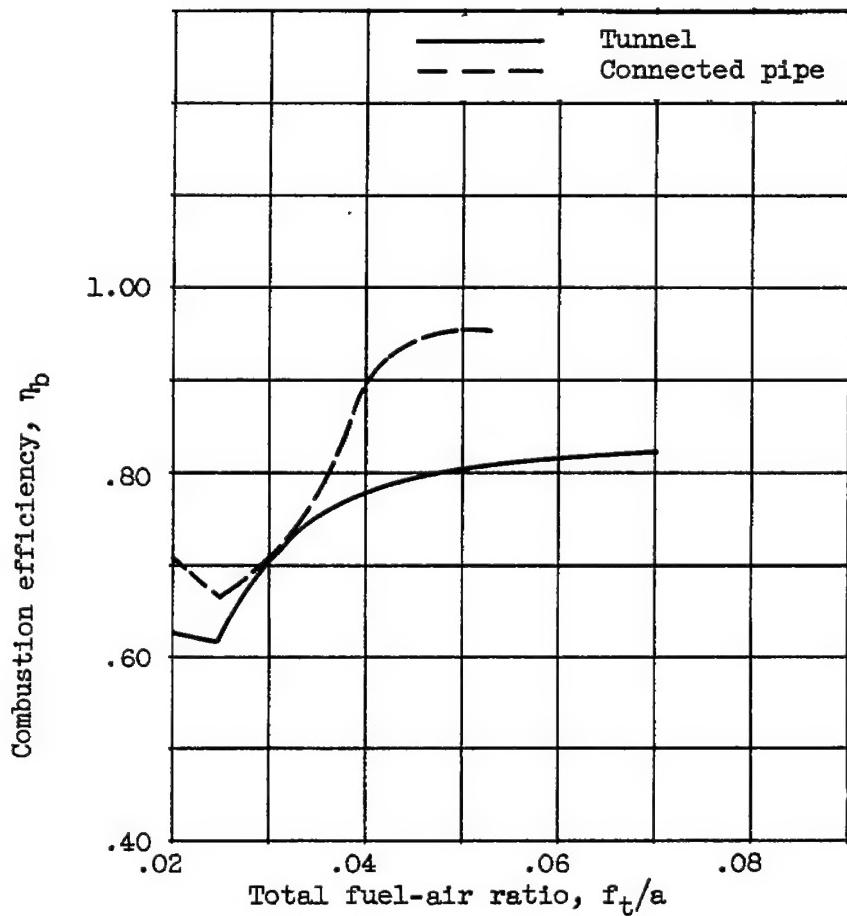
Figure 9. - Comparison of combustion effi-
ciency data obtained in various facilities.
Tunnel data: free-stream Mach number, 1.98;
temperature, 155° F; pressure, 2000 to 2900
pounds per square foot; velocity, 194 to
326 feet per second. Connected-pipe data:
temperature, 160° F; pressure, 2300 to 3800
pounds per square foot; velocity, 165 to
260 feet per second.

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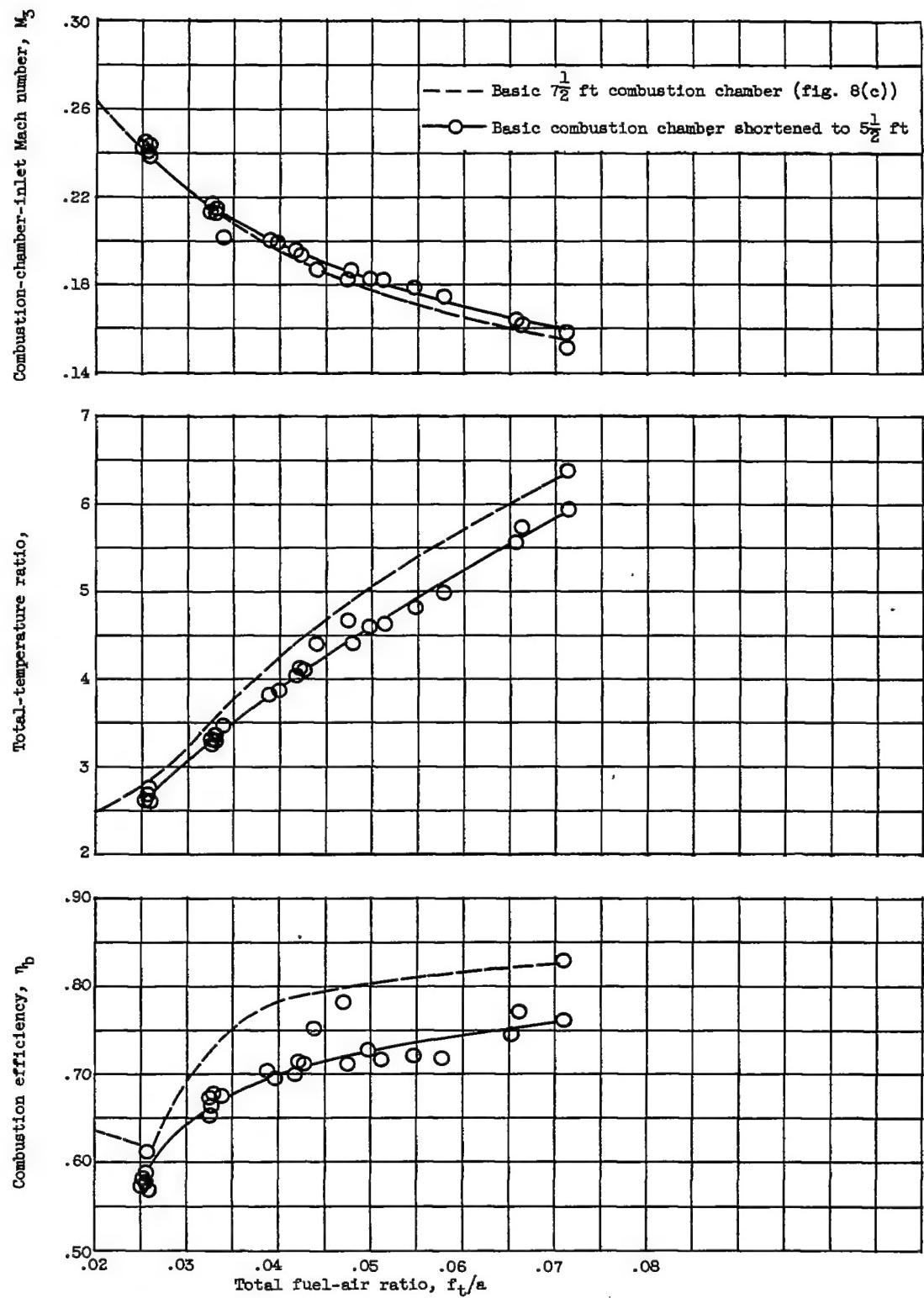
Figure 10. - Effect on combustor performance of shortening combustion-chamber length.

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(a) Total fuel-air ratio, 0.158; mass-flow ratio, 1.0.

(b) Total fuel-air ratio, 0.310; mass-flow ratio, 1.0.

(c) Total fuel-air ratio, 0.0455; mass-flow ratio, 0.958.

Total amplitude, lb/sq in.

○ Air-flow measuring, station x
□ Combustion-chamber inlet, station 3
◇ Nozzle inlet, station 5

Frequency, cps

(d) Total fuel-air ratio, 0.0490; mass-flow ratio, 0.915.
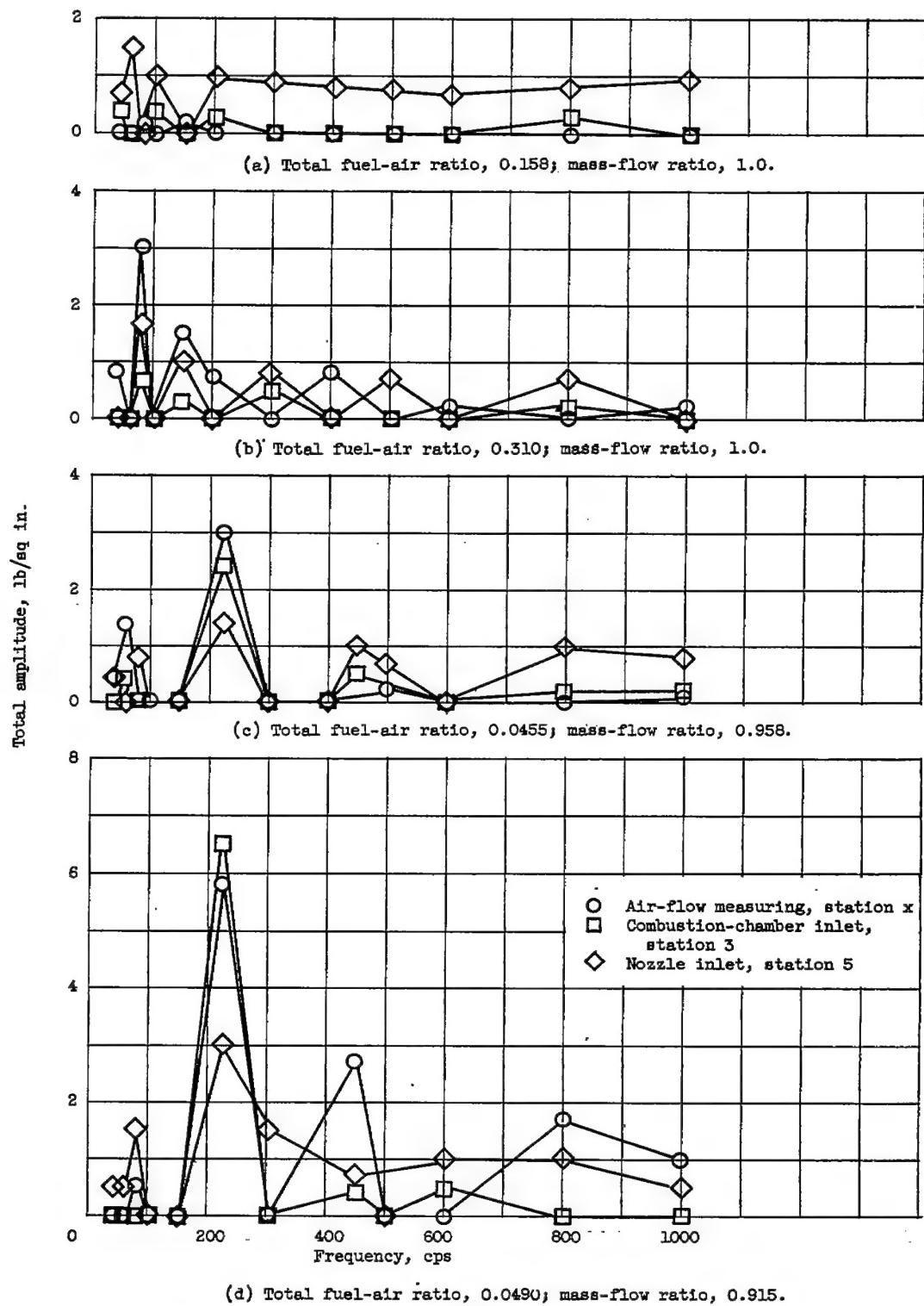
Figure 11. - Frequency, amplitude spectrums for various engine operating conditions. Free-stream Mach number, 2.16.

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(a) Free-stream Mach number, 1.79.

(b) Free-stream Mach number, 1.98.

(c) Free-stream Mach number, 2.16.
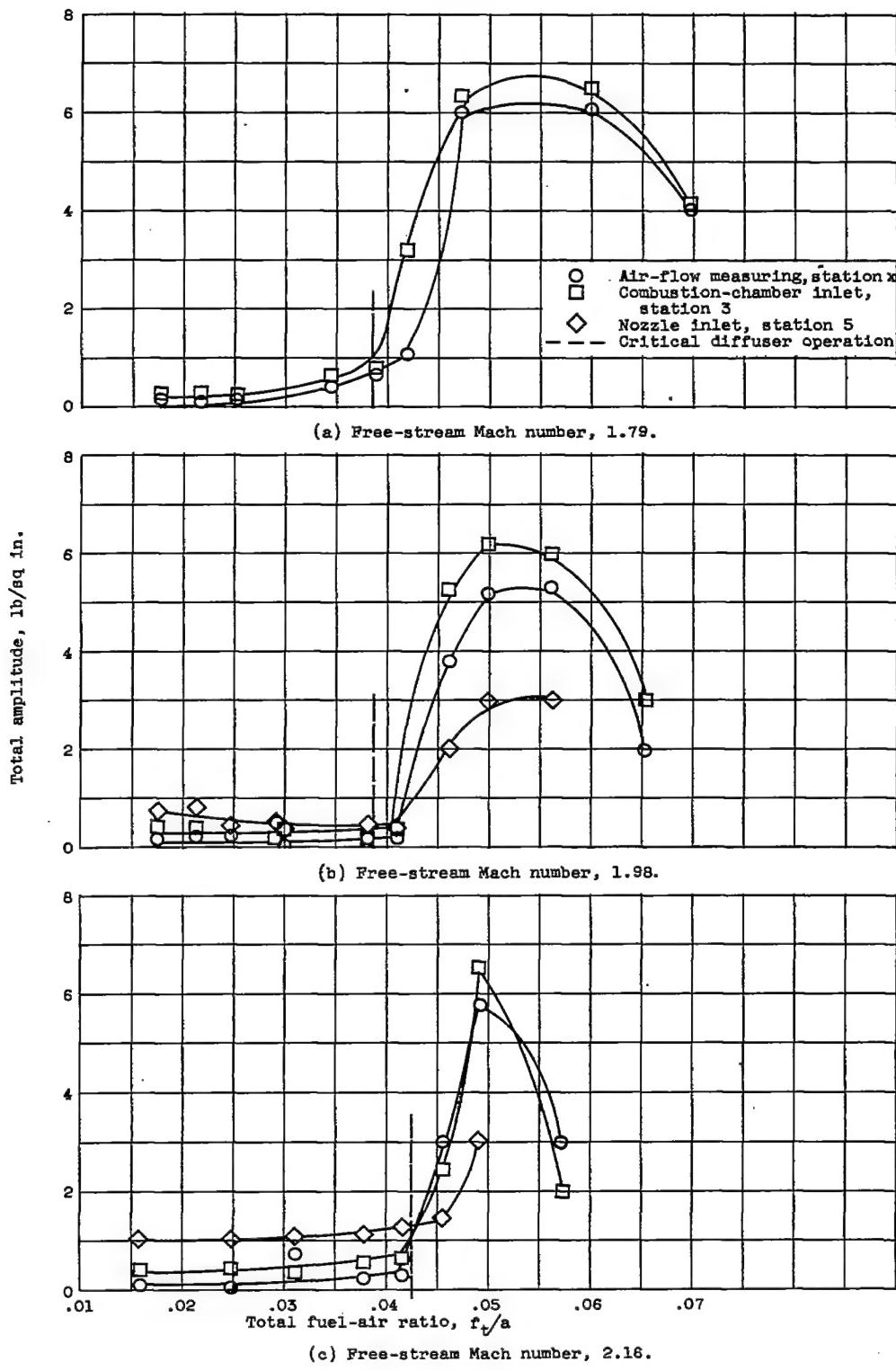
Figure 12. - Effect of free-stream Mach number on fuel-air-ratio, amplitude characteristics. Frequency, 225 ± 25 cycles per second.
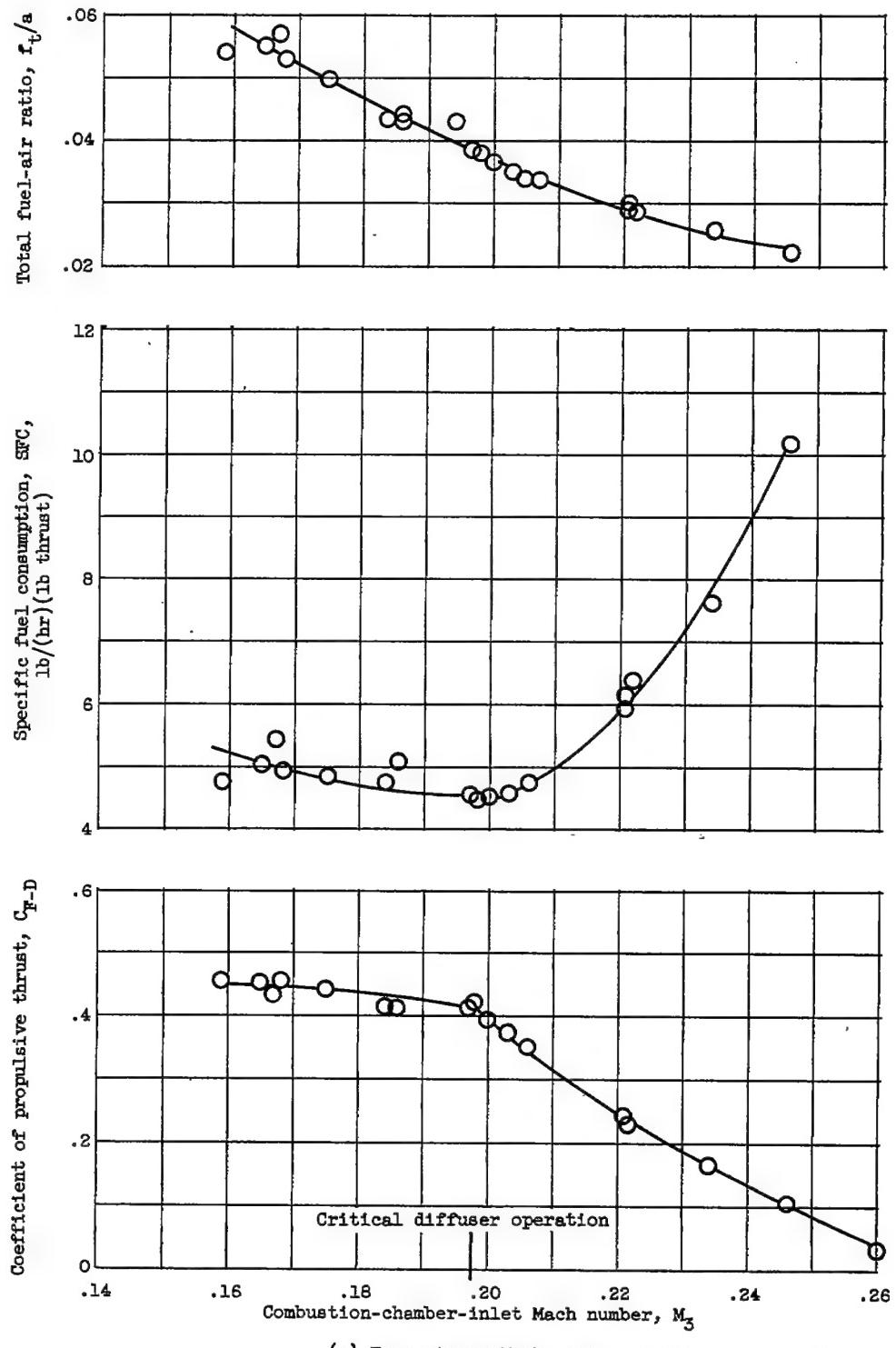
(a) Free-stream Mach number, 1.50.

Figure 13. - General engine performance.
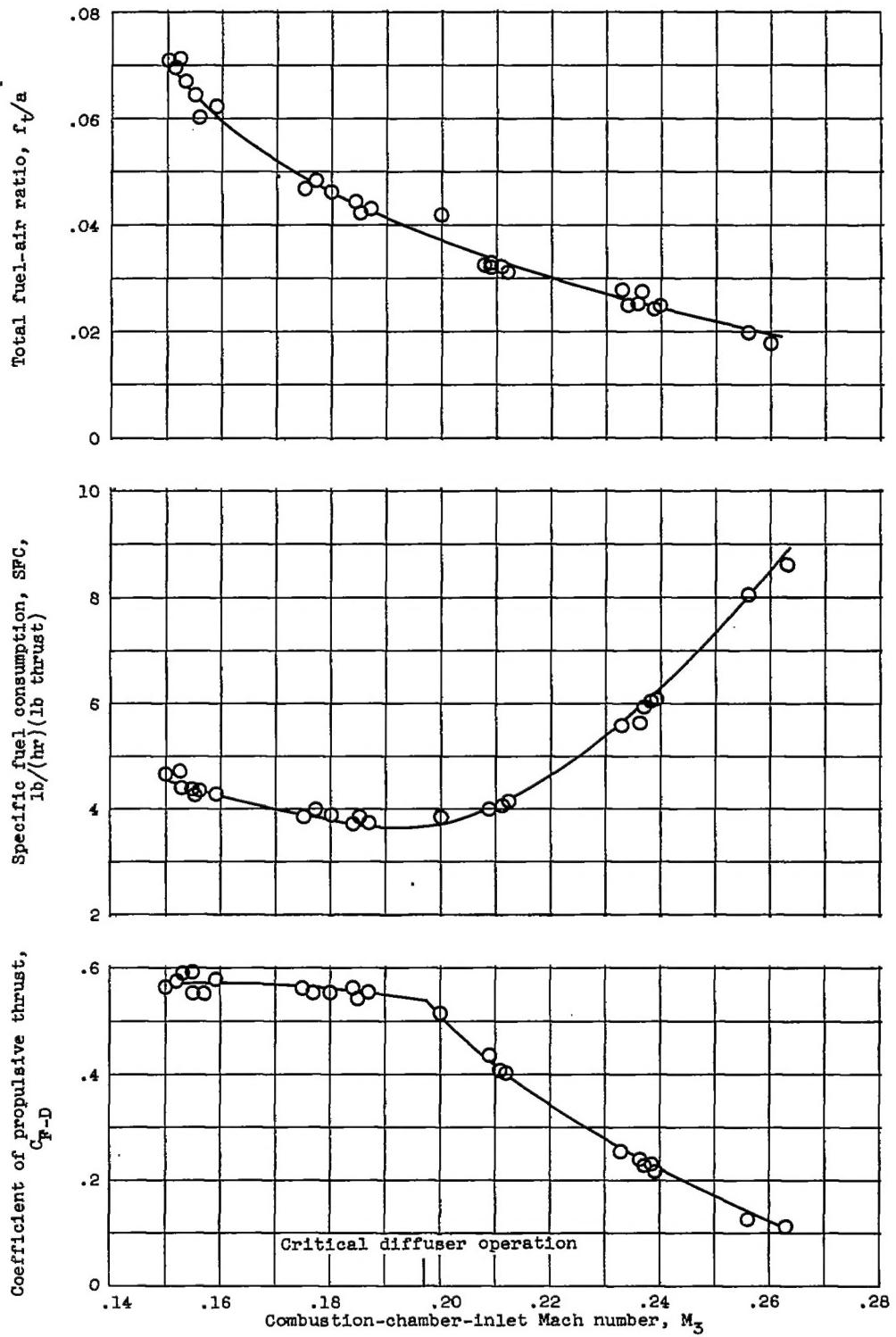
(b) Free-stream Mach number, 1.79.

Figure 13. - Continued. General engine performance.
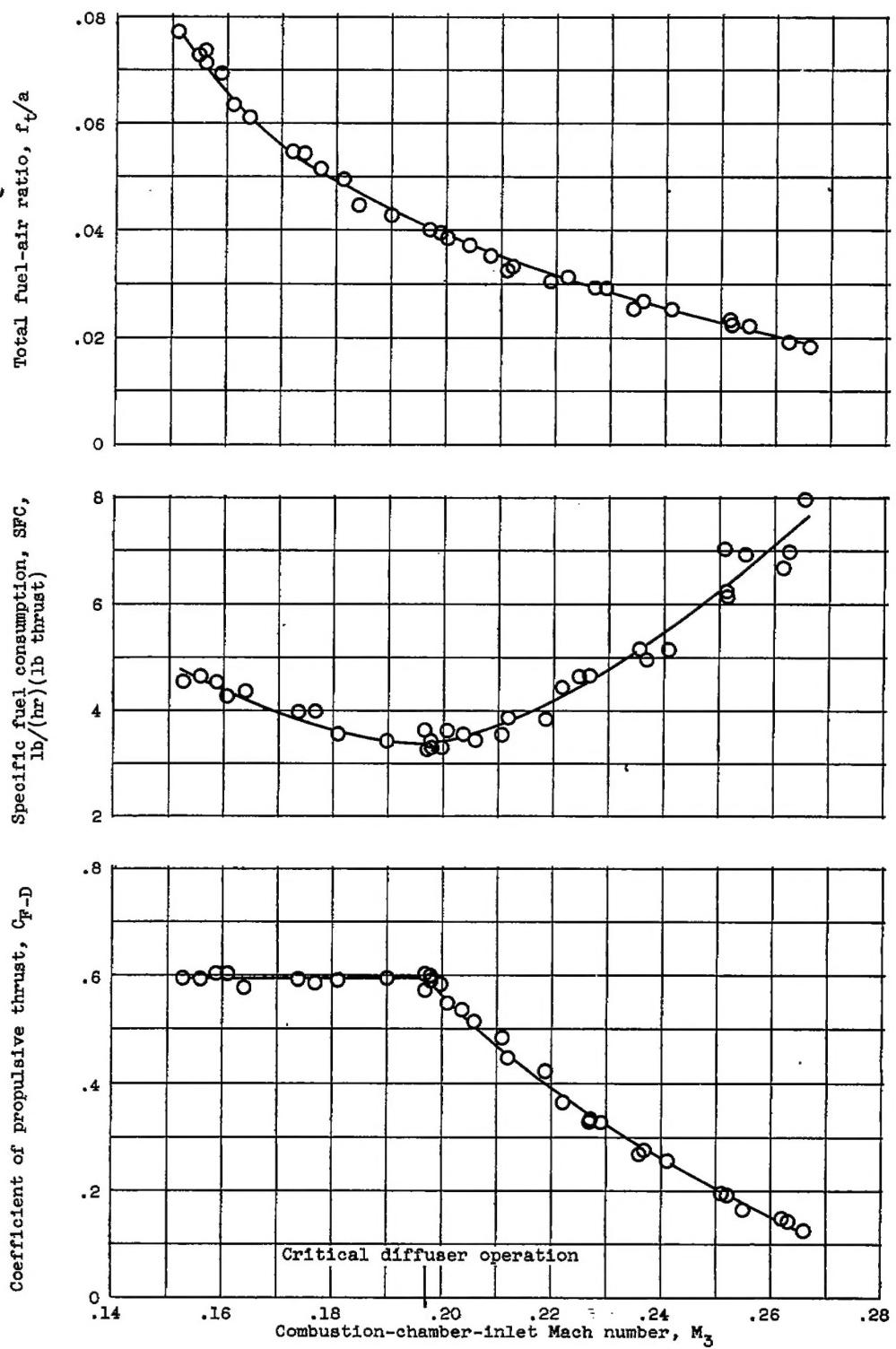
(c) Free-stream Mach number, 1.98.

Figure 13. - Continued. General engine performance.

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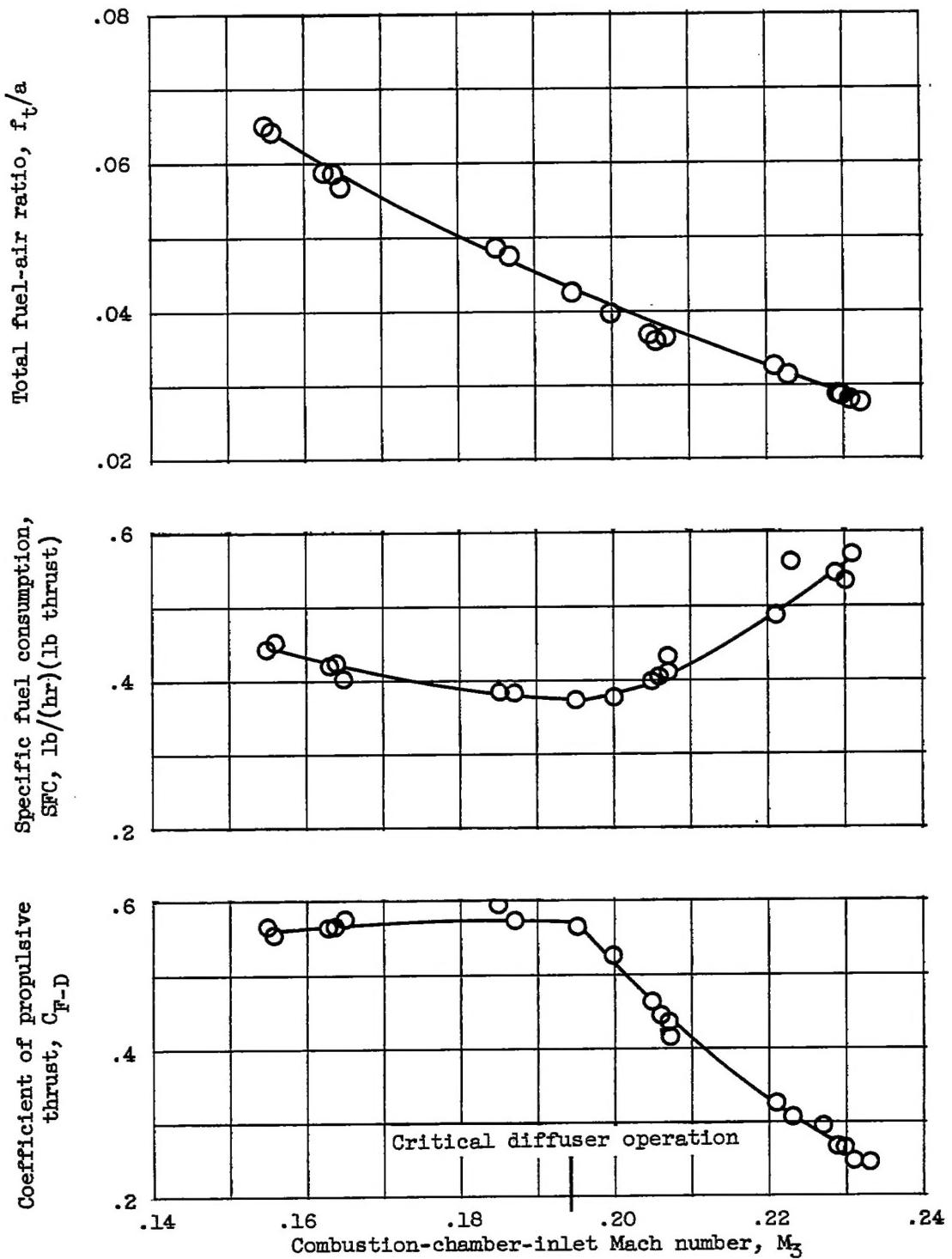
(d) Free-stream Mach number, 2.16.

Figure 13. - Concluded. General engine performance.
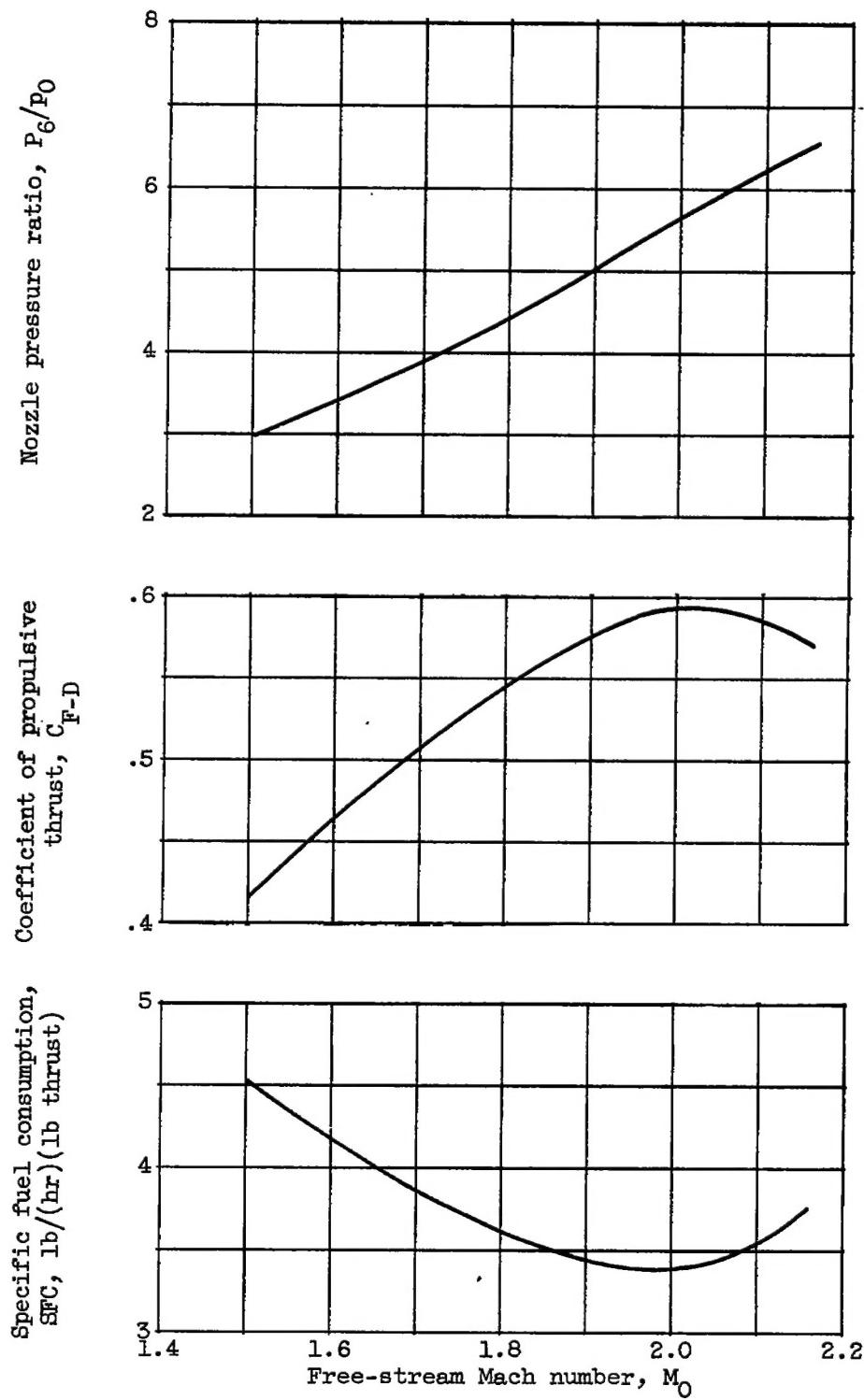
Figure 14. - Effect of Mach number on engine performance at critical inlet operation.